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Title: High-efficiency High-energy Photon Radiography Panels

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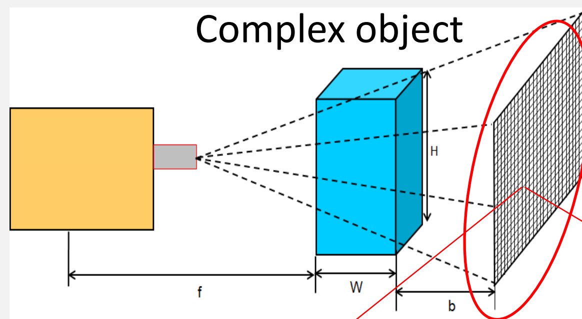
High-efficiency High-energy Photon Radiography Panels

TEAM
LBNL: Federico Moretti (PI), Edith Bourret, Stephen Derenzo, Didier Perrodin
LANL: Scott Watson, Nicola Winch
RMD Inc. : Matthew Marshall, Vivek Nagarkar, Bipin Singh

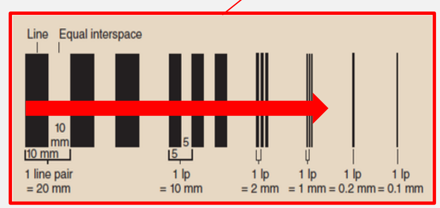
Introduction: High-Energy Radiography

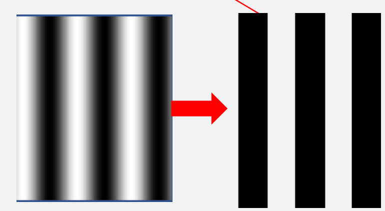
1-15 MeV photons are used for their capacity to penetrate dense and large objects, with applications from cargo scanning to security

High energy (up to several MeV) X-ray sources



- Portable panels
- Economical manufacturing
- Rugged





Need to improve image resolution and blur

Currently employed high-energy radiography panels technologies:

Medical radiography films, CR and DR panels → Cost → X-ray detection efficiency → (Pixelated) scintillator panels

Efficient radiography panels at reasonable production costs?

Project Goal and Approach

Goal:

- Demonstrate a developmental path towards production of efficient radiography panel for high energy radiography *while keeping the production cost reasonable.*
- Fulfill some needs identified in the research thrust GOR 2/K/b "Diagnostics systems".

Approach:

- Combination of simulations and experimental work and work with:
  1) LANL to ensure application driven requirements are integrated into the design options
  2) Radiation Monitoring Devices, Inc. (RMD) to provide prototype materials in columnar films for testing.

Challenge:

- Sources of a range of high energies bremsstrahlung photon compared to more common few hundred keV sources.
- **Find efficient/optimized compromise between fabrication cost and performance**

The Team: Role and Relevant Experience

LBNL:

F. Moretti, E. Bourret, S. Derenzo, D. Perrodin, D. Onken

- Detector panel simulations and synthesis
- Synthesis and characterization of scintillating materials, development of novel materials synthesis

LANL:

S. Watson and N, Winch

- Testing of small area samples with various sources
- Unique expertise from 30+ years of experience in high energy radiography, imaging techniques related to NNSA missions

RMD:

V. Nagarkar, M. Marshall, J. Wang, S. Miller, B. Singh

- Synthesis of large area scintillators in microcolumnar shape by Physical Vapor Deposition
- Over 20 years of R&D on radiography panel production and commercialization to both medical and non-medical x-ray imaging communities

Simulation with MCNP (1)

Initial simulations done to define detector designs and inform the experimental part:

Three different designs have been selected from baseline simulations and extensive previous ones from others

Design 1:

- Heavy scintillator (BGO) in W metal grid
- High detection efficiency, but high cost and low resolution

Design 2:

- Plastic scintillator (PVT) in Pb metal grid
- Intermediate detection efficiency, moderate cost, but low resolution

Design 3:

- Thick columnar storage plate on metal intensifier
- Low cost, large areas, relatively high resolution, but low detection efficiency

MCNP Simulation (2)

In-depth simulations on the three designs were done to:

- Understand the design parameters (e.g. best Pb grid wall thickness)
- Evaluate the expected performance as a function of x-ray beam energy
- Inform the experimental/synthesis effort

MCNP6.2 Monte Carlo software is used for these simulations to obtain

- The **line spread function** (LSF) and thus the **modulation transfer function** (MTF)
- The **noise power spectrum** (NPS)
- The **detection quantum efficiency** (DQE): combines 1) the ability to detect x-rays, 2) the spatial resolution, and 3) the image noise as a function of spatial frequency

for each design and parameter

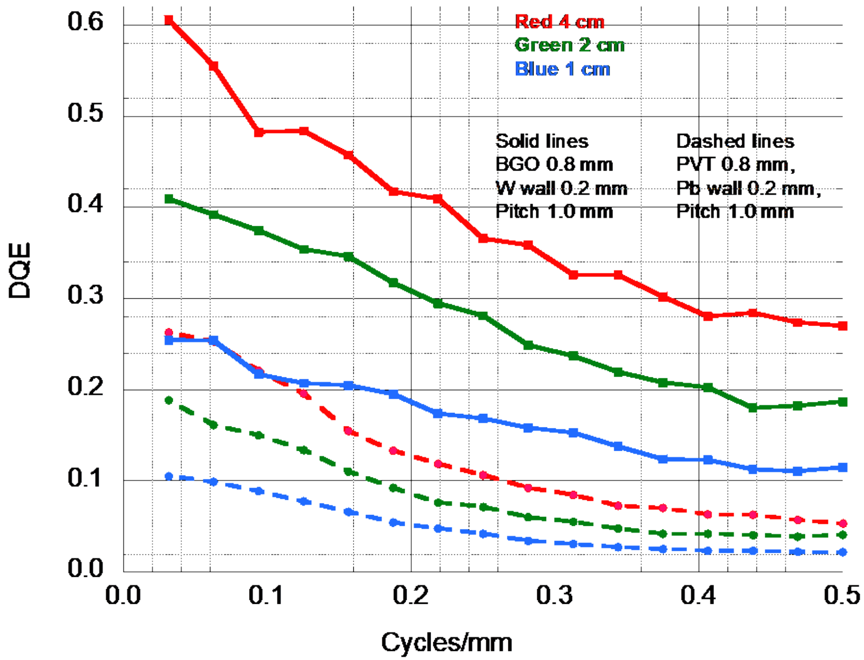
$$DQE(f) = \frac{\left(MTF(f)/N_{\text{point}}\right)^2}{\left(NPS(f)/N_{\text{flood}}\right)}$$

MCNP6.2 tally F6:E (energy deposited by e^-/e^+ in each pixel row) by (1) photoelectric interactions, (2) Compton scattering, (3) electron/positron pair production, (3) positron annihilation photons, and (5) bremsstrahlung interactions. All particles had a weight of one

Optical photon transport efficiency has not been simulated (but planned)

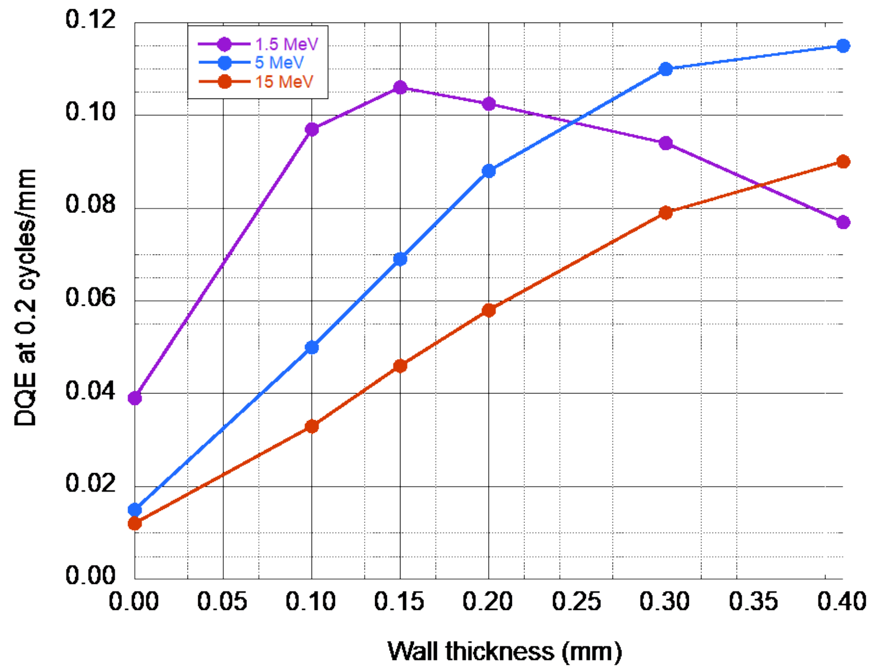
Simulations: Light or Heavy Scintillator in Metal Grid

5 MeV X-rays, panel thickness effect on DQE



Thicker panels provide almost linear improvement at all spatial frequencies

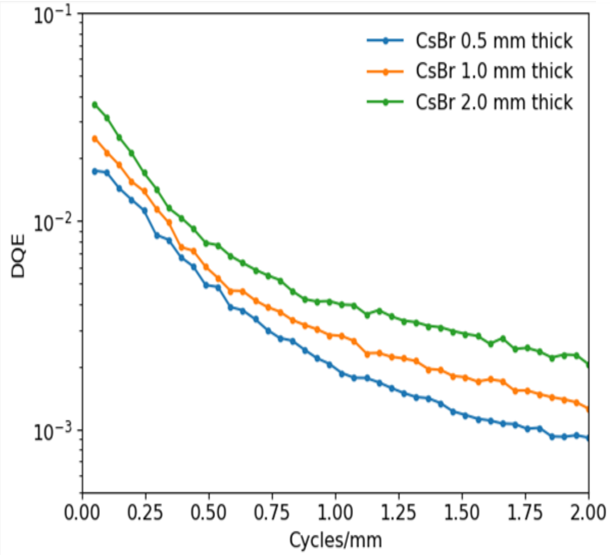
DQE of PVT/Pb at 0.2 cycles/mm vs wall thickness and X-ray energy

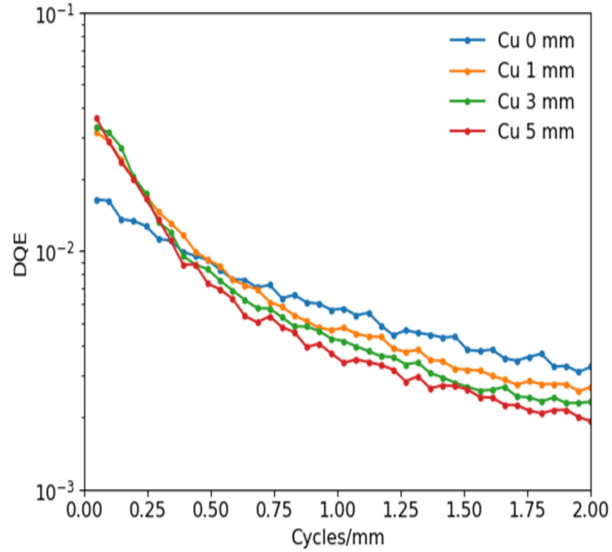


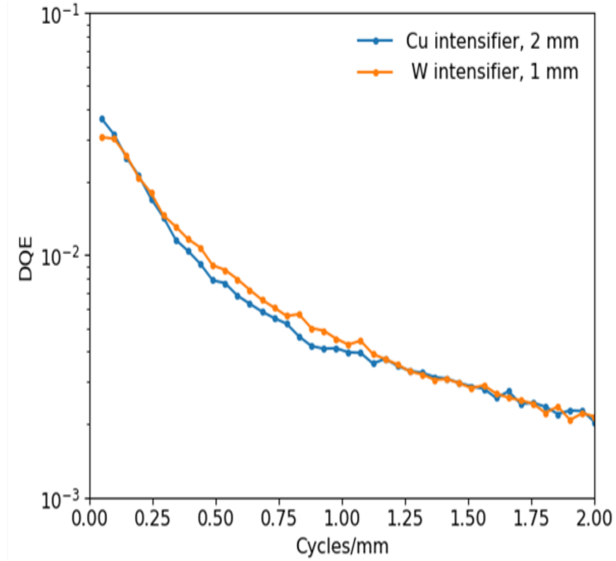
0.4 mm wall; low deposition in PVT (36% vol. 5% mass)

Note: pixel pitch 1 mm, BGO and PVT 0.8 mm
W and Pb wall 0.2 mm

Simulations: Storage Phosphors with Intensifier Foil







DQE vs CsBr thickness (@5 MeV)

- DQE improves as the thickness of the CsBr phosphor layer is increased.
- 2 mm thickness is good

DQE vs Cu thickness (@5 MeV)

- Slight dependence of DQE on metal intensifier
- For Cu, 1-3 mm is good

DQE vs metal (@5 MeV)

- Metal density has a role but it can be offset by choosing the appropriate thickness of the intensifier
- No need of very dense and expensive metals

Simulations: Conclusions and Outlook

Simulations work and experience from LANL have allowed us to determine three main directions for the experimental work

1. Plates using an array of pixels of scintillators:
   Dense scintillator pixels with reflectors
   BGO (1 x 1 x 20 mm pixels, separator ~0.1-0.2 mm)

2. Light scintillators in heavy metal grid
   Considering developed plastics or glass scintillators
   (1 x 1 x 20 mm pixels, dense metal grid ~0.1-0.2 mm)

3. Storage phosphor plate with metal intensifying foils
   (thicknesses: metal ~1 mm, CsBr ≧2 mm).
   These plates are currently made of thin films consisting of microcolumnar (about 10-40 µm) phosphor material and could be further improved with a thick film of more transparent structure via tailored vapor deposition.

Cost Consideration

1. Plates using an array of pixels of scintillators:

   Dense scintillator pixels with reflectors

   BGO crystal pixels: >250,000 pixels /per panel

   Labor intensive (pixels cut, polish and assembly)

2. Light scintillators in heavy metal grid

   Considering developed plastics or glass scintillators

   a. Use of existing commercialized grid
      - Both Pb and W are available form commercial sources
   b. Determination that PVT can fit the needs

3. Storage phosphor plate with metal intensifying foils

   a. Large area deposition/ thick films
   c. Intensifying screens are available and inexpensive (metallic plates)

Experimental Studies

Simulations work and experience from LANL have allowed us to determine three main directions for the experimental work

Started

1. Plates using an array of pixels of scintillators:
   Dense scintillator pixels with reflectors
   BGO (1 x 1 x 20 mm pixels, separator ~0.1-0.2 mm)

On-going

2. Light scintillators in heavy metal grid
   Considering developed plastics or glass scintillators
   (1 x 1 x 20 mm pixels, dense metal grid ~0.1-0.2 mm)

3. Storage phosphor plate with metal intensifying foils
   (thicknesses: metal ~1 mm, CsBr ≧2 mm).
   These plates are currently made of thin films consisting of microcolumnar (about 10-40 µm) phosphor material and could be further improved with a thick film of more transparent structure via tailored vapor deposition.

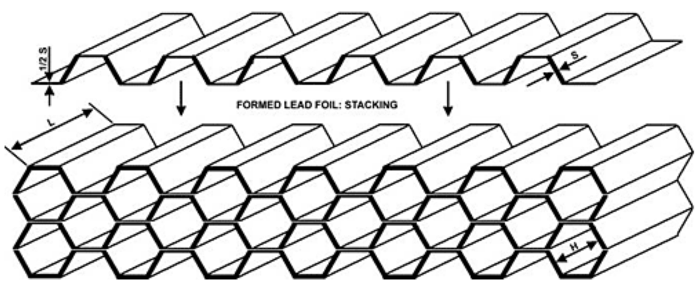
Light Scintillator in Heavy Metal Grid: PVT in Pb

PVT kit BC-490 from Saint-Gobain **+**

Resin: Pre-polymerized plastic phosphor
Catalyst: Unspecified
Solvent: Vinyltoluene monomer

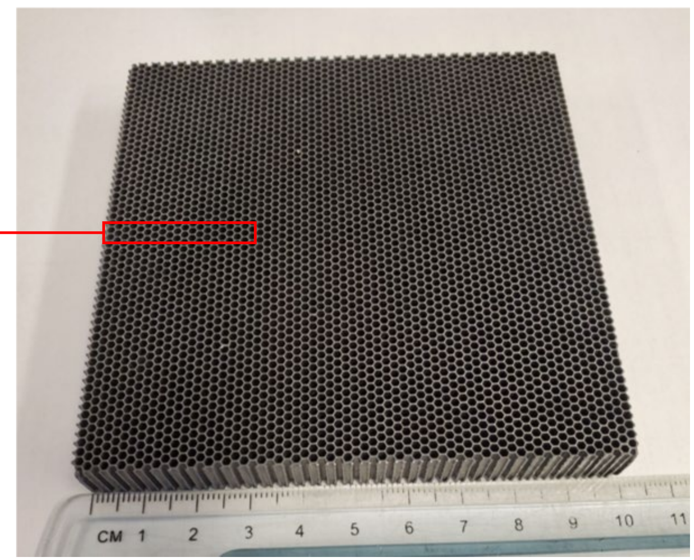
Lead grid (commercially available)

- Corrugated lead grid: Nuclear Medicine collimator with hexagonal channels
- Shaped for uniform wall thickness
- When filled with PVT expected effective imaging with 1-2 cycle/mm resolution



Inside hexagonal side length: 0.88 mm
Wall thickness is 0.24 mm

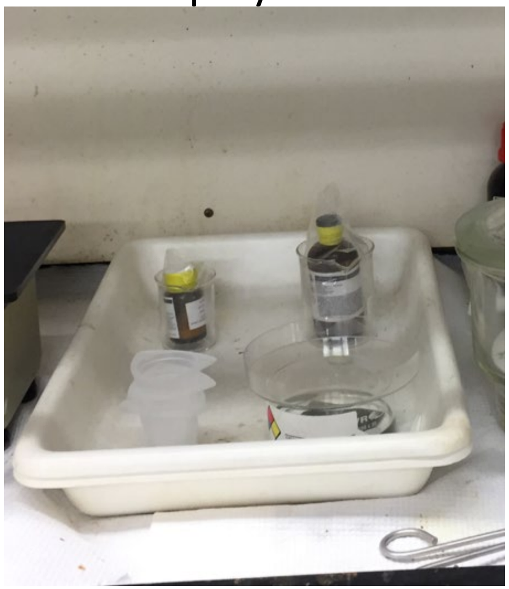
Note: Cast lead grids must be used to avoid detrimental reaction with epoxy



4x4x0.5 inch^3

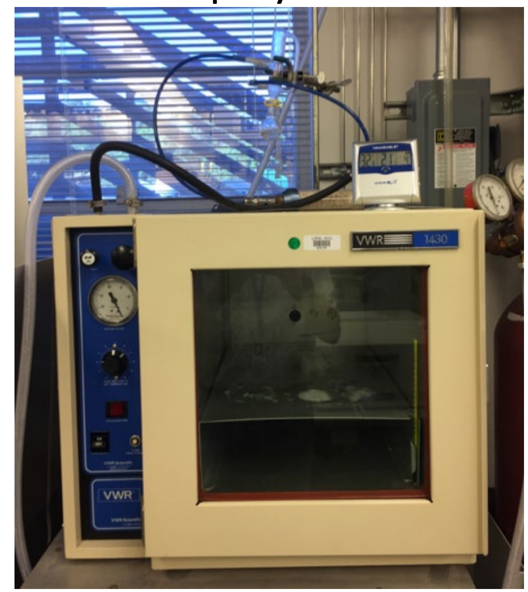
Baseline Experiment

1. Standard polymer chemistry

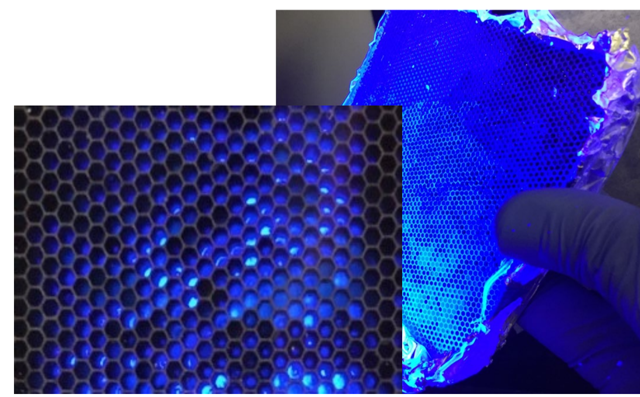


2. Degassing

3. Low T polymerization



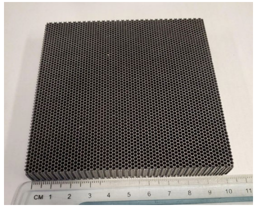
Defining process parameters for clear, uniform PVT in each Pb channel

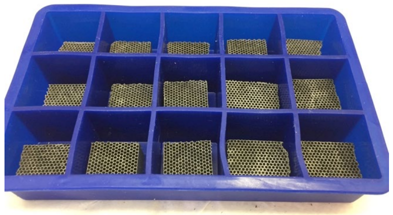


Polymerization takes ~20 days

New Protocol Definition and Results

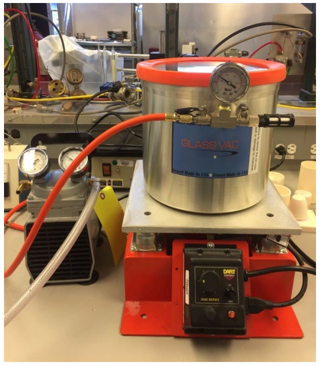
Use of mini grids: 4x4x0.5” grid cleaned and cut in smaller pieces of roughly 1x1x0.5”





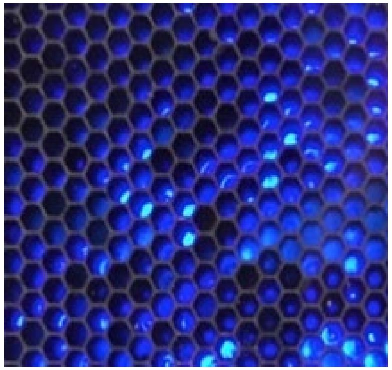
Process parameters	Set by manufacturer	To be defined
Product concentrations	Yes	
Room temperature degassing	No	Time Vacuum level
Pouring into grid	No	Timing
Filled grid degassing	No	Time Vacuum level
Polymerization	Guidelines 47˚C, 14 days, inert atmosphere	Time Temperature
Final curing	Guidelines 80˚C, 8 hours, inert atmosphere	Time Temperature

Controlled processing tools

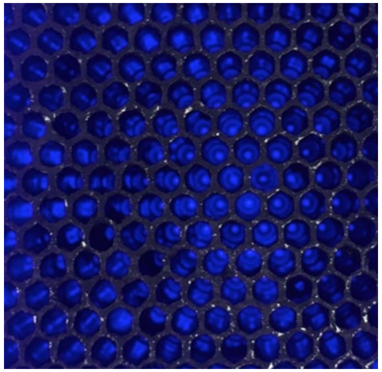


Vacuum chamber on vibrating table

Atmosphere and temperature controlled oven



BEFORE

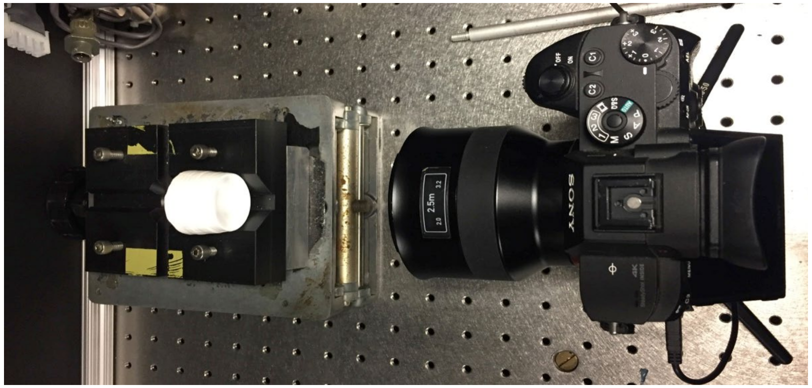


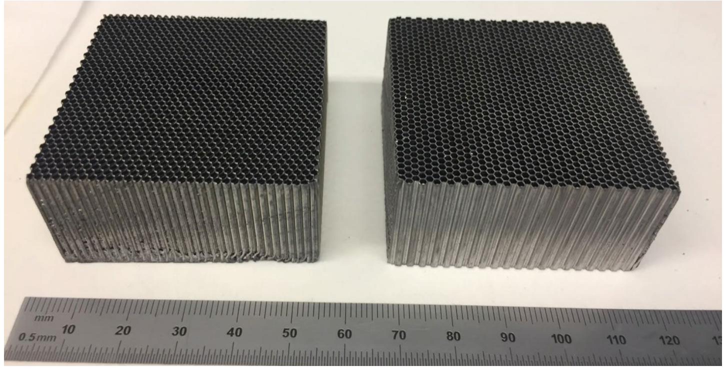
AFTER

Characterization and Next Steps

First samples characterization in progress:

- X-ray excited luminescence data to be acquired on last sample
- Small imaging set-up installed and now being tested; currently using ^{137}Cs and ^{60}Co sources
- New larger grids will be ready for imaging tests at LANL in FY21 Q3





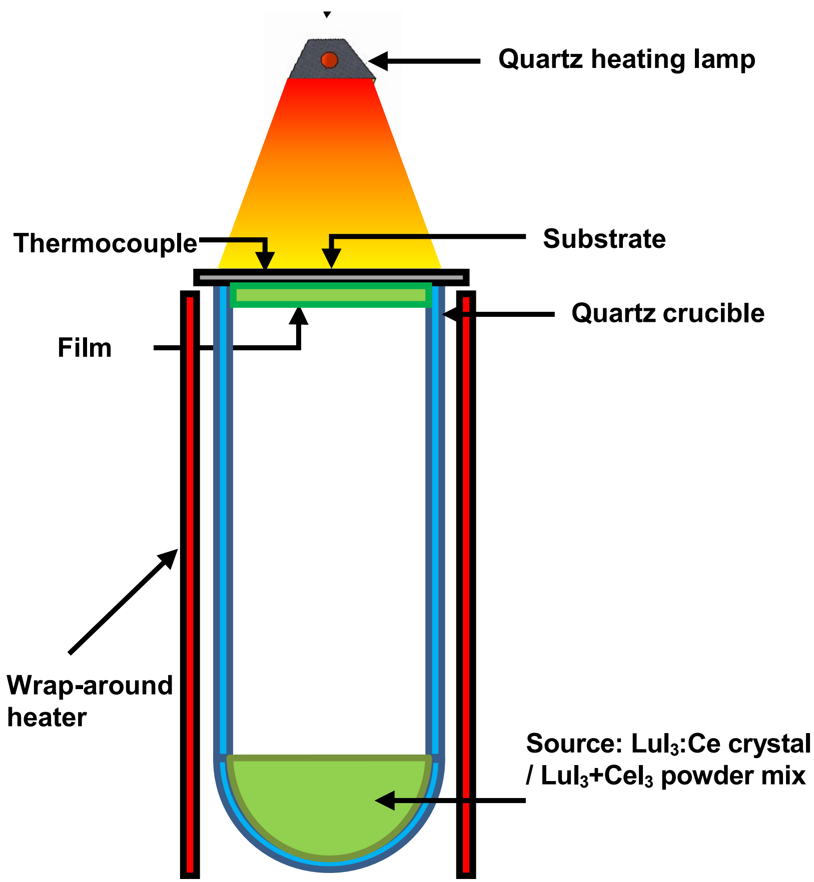
Storage Phosphor Plate with Intensifying Foil

Physical Vapor Deposition of the low-cost well-understood CsBr:Eu storage phosphor:

- Modify by incorporating Eu dopant ions in optimal concentrations
- Deposited by thermal evaporation to produce columnar films
- Columnar structure preserves spatial resolution

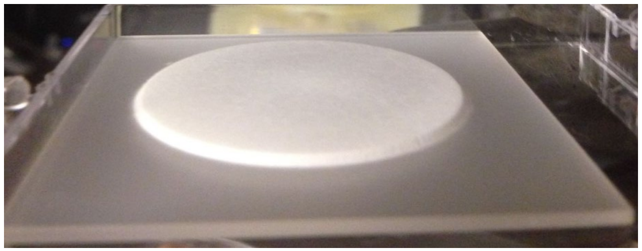
Low-hygroscopicity of CsBr:Eu makes for robust screens.

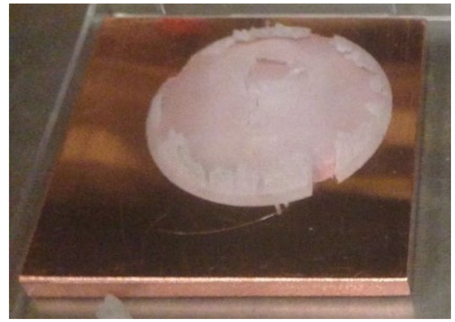
Well known deposition method used in the production of CsI:Tl medical radiography panels

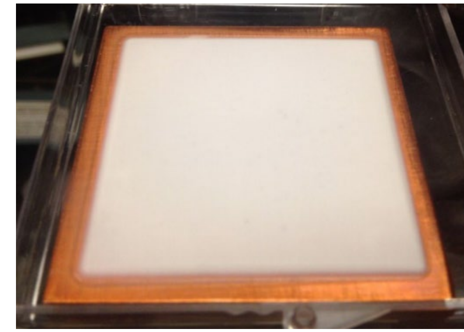


Synthesis at RMD Inc.

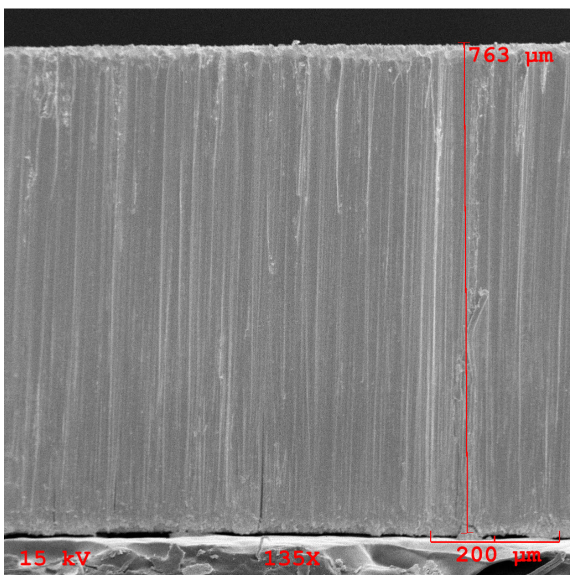
- Optimizing deposition parameters, thickness, dopant concentration, microcolumnar layer uniformity, and adhesion to substrates



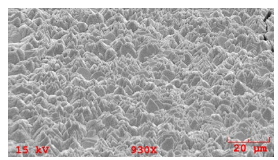




- Layer structure - Scanning Electron Microscopy

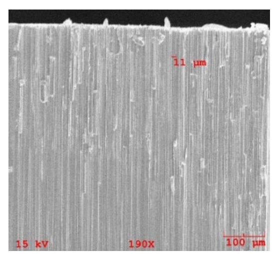


Top



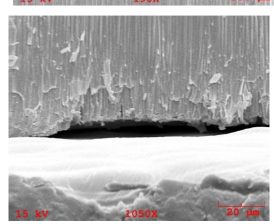
Top view: Densely packed pointy columns, approaching density of CsBr:Eu crystals

Middle



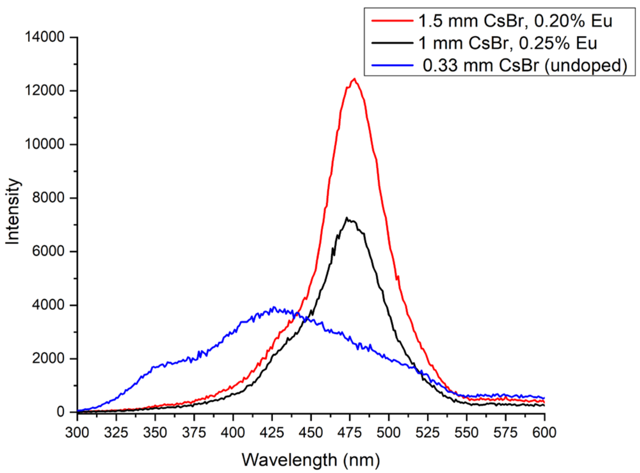
Approx. 10 μm column diameter

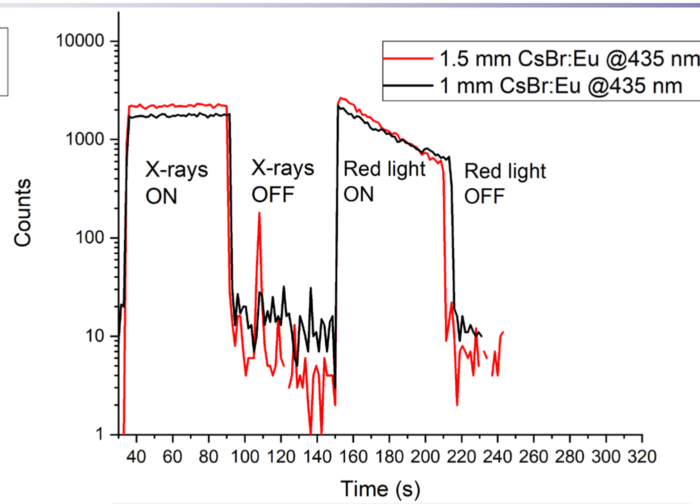
Bottom

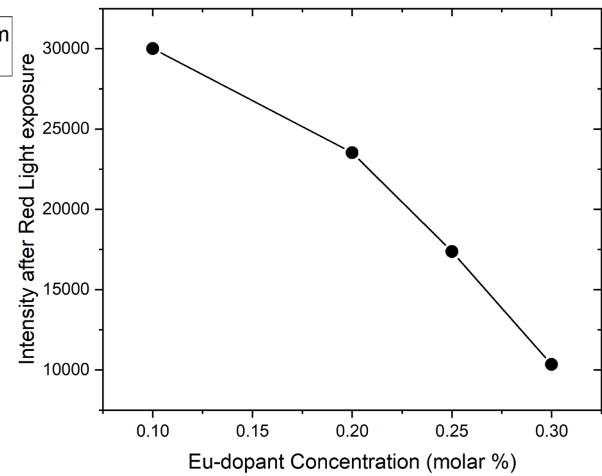


No amorphous layer at the bottom, good nucleation

Characterization







X-ray excited luminescence

- Clear dependence of spectrum upon Eu addition in raw materials
- Signal increases with film thickness
- Grown film response seems to be rather uniform
- Expected sample darkening after irradiation due to population of traps needed for storage ability

Photo-Stimulated Luminescence

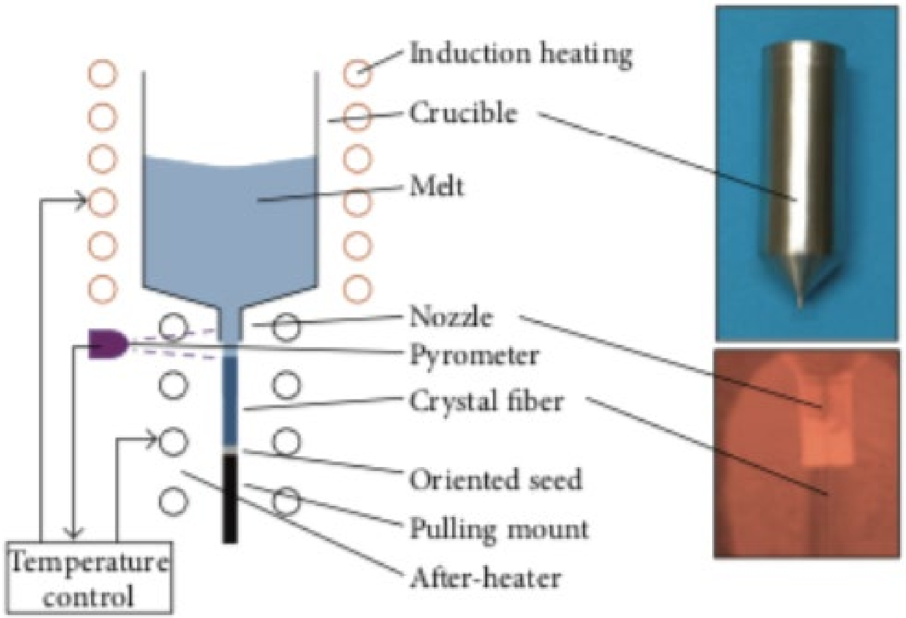
- Clear PSL signal during illumination with red LED after X-ray irradiation
- Low afterglow after X-ray irradiation: the traps are stable at room T
- Best PSL excitation wavelength still to be determined

PSL Intensity vs Eu content

- Initial results on Eu concentration optimization
- PSL Intensity decreases by increasing Eu concentration
- Best Eu concentration is still being investigated

Heavy Scintillator in Metal Grid

Fabrication of BGO pixels to be assembled in plates



Micro-pulling down growth of single crystal rods

Less expensive than pixel fabrication from large single crystal boules

Several issues to be solved:

- BGO melt "sticks" to the crucible: difficult growth of uniform sized rods
- Material and shape of the crucible has yet to be determined

Possible alternative:

Direct growth of BGO crystals in a metal grid may be possible, though panel tiling will likely be necessary to contain fabrication costs

Overall Conclusions and Next Steps

Timeline

Initial Project Review

↓

Simulations

↓

Fabrication
LBNL
RMD

↓

Testing

Task	Year 1				Year 2				Year 3				Year 4	
	Q 1	Q 2	Q 3	Q 4	Q 1	Q 2	Q 3	Q 4	Q 1	Q 2	Q 3	Q 4	Q 1	Q 2
Task 1: Project Baseline Review	Completed													
Task 2: Simulation of response of detector material to high-energy X-rays	Completed	Completed	Completed	Completed	Completed	Completed								
Task 3: Material selection, synthesis and characterization at LBNL	Completed	Completed	Completed	Completed	Completed	Completed	Planned	Planned	Planned	Planned	Planned	Planned		
Task 4: Micro-columnar growth at RMD		Admin delays	Completed	Completed	Completed	Completed	Planned	Planned	Planned	Planned	Planned	Extension		
Task 5: Material testing at LANL					Admin delays	Admin delays	Planned	Planned	Planned	Planned	Planned	Planned		
Task 6: Independent Assessment						Planned								
Task 7: Write final report, provides deliverables and Final Out Brief											Planned	Planned	Planned	

Planned   Completed   Admin delays   Extension

The project is pretty much on-time despite the difficulties encountered during the emergency